Lorentz symmetry violation and high-energy cosmic rays

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We discuss possible violations of Poincaré's relativity principle at energy scales close to Planck scale and point out the potentialities of high-energy cosmic-ray physics to uncover these new phenomena.

1. THE RELATIVITY PRINCIPLE: A BASIC PHYSICS ISSUE BEHIND A DEBATE ON PRIORITY

H. Poincaré was the first author to consistently formulate the relativity principle stating in 1895 [1]:

"Absolute motion of matter, or, to be more precise, the relative motion of weighable matter and ether, cannot be disclosed. All that can be done is to reveal the motion of weighable matter with respect to weighable matter"

The deep meaning of this law of Nature was further emphasized when he wrote [2]:

"This principle will be confirmed with increasing precision, as measurements become more and more accurate"

The role of H. Poincaré in building relativity, and the relevance of his thought, have often been emphasized [3,4]. In his June 1905 paper [5], published before Einsteins's article [6] arrived (on June 30) to the editor, he explicitly wrote the relativistic transformation law for the charge density and velocity of motion and applied to gravity the "Lorentz group", assumed to hold for "forces of whatever origin". However, his priority is sometimes denied [7,8] on the grounds that *"Einstein essentially announced the failure of all ether-drift experiments past and future as a foregone conclusion, contrary to Poincaré's empirical bias"* [7], that Poincaré did never *"disavow the ether"* [7] or that *"Poincaré never challenges... the absolute time of newtonian mechanics... the ether is not only the absolute space of mechanics... but a dynamical entity"* [8]. It is implicitly assumed that A. Einstein was right in 1905 when *"reducing ether to the absolute space of mechanics"* [8] and that H. Poincaré was wrong because *"the ether fits quite nicely into Poincaré's view of physical reality: the ether is real..."* [7]. But modern particle physics has brought back the concept of a non-empty vacuum where free particles propagate: without such an "ether" where fields can condense, the standard model of electroweak interactions could not be written and quark confinement could not be understood. Modern cosmology is not incompatible with an "absolute local frame" close to that suggested by the study of cosmic microwave background radiation. Then, the relativity principle would become a symmetry, a concept whose paternity was attributed to H. Poincaré by R.P. Feynman [9]:

"Precisely Poincaré proposed investigating what could be done with the equations without altering their form. It was precisely his idea to pay attention to the symmetry properties of the laws of physics"

As symmetries in particle physics are in general violated, Lorentz symmetry may be broken and an absolute local rest frame may be detectable through experiments performed beyond the relevant scale. Poincaré's special relativity (a symmetry applying to physical processes) could live with this situation, but not Einstein's approach such as it was formulated in 1905 (an absolute geometry of space-time that matter cannot escape). But, is Lorentz symmetry broken? We discuss here two issues: a) the scale where we may expect Lorentz symmetry to be violated; b) the physical phenomena and experiments potentially able to uncover Lorentz symmetry violation (LSV). Previous papers on the subject are references [10] to [16] and references therein.

2. SPECIAL RELATIVITY AS A LOW-ENERGY LIMIT

Low-energy tests of special relativity have cosfirmed its validity to an extremely good accuracy, but the situation at very high energy remains more uncertain (see [10] to [16]). If Lorentz symmetry violation (LSV) follows a E^2 law ($E =$ energy), similar to the effective gravitational coupling, it can be $\approx\ 1$ at $E\ \approx\ 10^{21}\ eV$ and $\approx\ 10^{-26}$ at $E\ \approx\ 100\ MeV$ (corresponding to the highest momentum scale involved in nuclear magnetic resonance experiments), in which case it will escape all existing low-energy bounds. If LSV is $\approx\ 1$ at Planck scale ($E\ \approx\ 10^{28}\ eV$), and following a similar law, it will be $\approx\ 10^{-40}$ at $E\ \approx\ 100\ MeV$. Our suggestion is not in contradiction with Einstein's thought such as it became after he had developed general relativity. In 1921 , A. Einstein wrote in "Geometry and Experiment": *"The interpretation of geometry advocated here cannot be directly applied to submolecular spaces... it might turn out that such an extrapolation is just as incorrect as an extension of the concept of temperature to particles of a solid of molecular dimensions"*. It is remarkable that special relativity holds at the attained accelerator energies, but there is no fundamental reason for this to be the case above Planck scale.

A typical example of models violating Lorentz symmetry at very short distance is provided by models where an absolute local rest frame exists and non-locality in space is introduced through a fundamental length scale a [11]. Such models lead to a deformed relativistic kinematics of the form [11,16]:

$$E\ =\ (2\pi)^{-1}\ h\ c\ a^{-1}\ e\ (k\ a) \tag{1}$$

where h is the Planck constant, c the speed of light, k the wave vector and $[e\ (k\ a)]^2$ is a convex function of $(k\ a)^2$ obtained from vacuum dynamics. Expanding equation (1) for $k\ a\ \ll\ 1$, we can write:

$$e\ (k\ a)\ \ \simeq\ \ [(k\ a)^2\ -\ \alpha\ (k\ a)^4 + (2\pi\ a)^2\ h^{-2}\ m^2\ c^2]^{1/2} \tag{2}$$

m being the mass, α a model-dependent constant $\approx 0.1\ -\ 0.01$ for full-strength violation of Lorentz symmetry at momentum scale $p\ \approx\ a^{-1}\ h$, and:

$$E\ \ \simeq\ \ p\ c\ +\ m^2\ c^3\ (2\ p)^{-1} -\ p\ c\ \alpha\ (k\ a)^2/2 \tag{3}$$

The "deformation" $\Delta\ E\ =\ -\ p\ c\ \alpha\ (k\ a)^2/2$ in the right-hand side of (3) implies a Lorentz symmetry violation in the ratio $E\ p^{-1}$ varying like $\Gamma\ (k)\ \simeq\ \Gamma_0\ k^2$ where $\Gamma_0\ =\ -\ \alpha\ a^2/2$. If c and α are universal parameters for all particles, LSV does not lead to the spontaneous decays predicted in [17]: the existence of very high-energy cosmic rays cannot be regarded as an evidence against LSV. With the deformed relativistic kinematics (DRK) defined by (1)-(3), Lorentz symmetry remains valid in the limit $k\ \rightarrow\ 0$, contrary to the standard $TH\epsilon\mu$ model [18]. The above non-locality may actually be an approximation to an underlying dynamics involving superluminal particles [10,12,15,16], just as electromagnetism looks nonlocal in the potential approximation to lattice dynamics in solid-state physics: it would then correspond to the limit $c\ c_i^{-1}\ \rightarrow\ 0$ where c_i is the superluminal critical speed.

Are c and α universal? This may be the case for all "elementary" particles, i.e. quarks, leptons, gauge bosons..., but the situation is less obvious for hadrons, nuclei and heavier objects. From a naive soliton model [11], we inferred that: a) c is expected to be universal up to very small corrections ($\sim\ 10^{-40}$) escaping all existing bounds; b) an approximate rule can be to take α universal for leptons, gauge bosons and light hadrons (pions, nucleons...) and assume a $\alpha \propto m^{-2}$ law for nuclei and heavier objects, the nucleon mass setting the scale.

3. THE RELEVANCE OF COSMIC-RAY EXPERIMENTS

If Lorentz symmetry is broken at Planck scale or at some other fundamental length scale, the effects of LSV may be observable well below this energy: they can produce detectable phenomena at the highest observed cosmic ray energies. This is due to DRK [11,13,14]: at energies above $E_{trans}\ \approx\ \pi^{-1/2}\ h^{1/2}\ (2\ \alpha)^{-1/4}\ a^{-1/2}\ m^{1/2}\ c^{3/2}$, the very small deformation $\Delta\ E$ dominates over the mass term $m^2\ c^3\ (2\ p)^{-1}$ in (3) and modifies all kinematical balances. Because of the negative value of $\Delta\ E$, it costs more and more energy, as energy increases above E_{trans}, to split the incoming logitudinal momentum. The parton model (in any version), as well as standard formulae for Lorentz contraction and time dilation, are also ex-

pected to fail above this energy [11,16] which corresponds to $E \approx 10^{20}$ eV for $m =$ proton mass and α $a^2 \approx 10^{-72}$ cm^2 (f.i. $\alpha \approx 10^{-6}$ and $a =$ Planck length), and to $E \approx 10^{18}$ eV for $m =$ pion mass and α $a^2 \approx 10^{-67}$ cm^2 (f.i. $\alpha \approx 0.1$ and a = Planck length). Assuming that the earth moves slowly with respect to the absolute rest frame (the "vacuum rest frame"), these effects lead to observable phenomena in future experiments devoted to the highest-energy cosmic-rays:

a) For α $a^2 > 10^{-72}$ cm^2 , and assuming a universal value of α , there is no Greisen-Zatsepin-Kuzmin cutoff for the particles under consideration and cosmic rays (e.g. protons) from anywhere in the presently observable Universe can reach the earth.

b) With the same hypothesis, unstable particles with at least two stable particles in the final states of all their decay channels become stable at very high energy. Above E_{trans}, the lifetimes of all unstable particles (e.g. the π^0 in cascades) become much longer than predicted by relativistic kinematics.

c) In astrophysical processes at very high energy, similar mechanisms can inhibit radiation under external forces, GZK-like cutoffs, decays, photodisintegration of nuclei, momentum loss through collisions, production of lower-energy secondaries... potentially contributing to solve all basic problems raised by the highest-energy cosmic rays.

d) With the same hypothesis, the allowed final-state phase space of two-body collisions is modified and can lead to a sharp fall of cross-sections for incoming cosmic ray energies above $E_{lim} \approx (2\ \pi)^{-2/3}\ (E_T\ a^{-2}\ \alpha^{-1}\ h^2\ c^2)^{1/3}$, where E_T is the energy of the target. As a consequence, and with the previous figures for Lorentz symmetry violation, above some energy E_{lim} between 10^{22} and 10^{24} eV a cosmic ray will not deposit most of its energy in the atmosphere and can possibly fake an exotic event with much less energy.

e) Effects a) to d) are obtained using only DRK. If dynamical anomalies are added (failure, at very small distance scales, of the parton model and of the standard Lorentz formulae for length and time...), we can expect much stronger effects in the cascade development profiles of cosmic-ray events.

f) Cosmic superluminal particles would produce atypical events with very small total momentum, isotropic or involving several jets [10,12,15,16].

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